MAXIMUM POWER POINT TRACKING USING LLC RESONANT CONVERTER FOR PV POWER SYSTEMS

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MAXIMUM POWER POINT TRACKING USING LLC RESONANT CONVERTER FOR PV POWER SYSTEMS

by

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LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
CC	Constant Current
CV	Constant Voltage
DC	Direct Current
EMI	Electromagnetic Interference
FHA	First Harmonic Approximation
INC	Incremental Conductance
LLC-SRC	LLC Series Resonant Converter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
OECD	Organization for Economic Cooperation and Development
P&O	Perturb and Observe
PV	Photovoltaic
PRC	Parallel Resonant Converter
PWM	Pulse-Width Modulation
RMS	Root Mean Square
SEPIC	Single-Ended Primary Inductor Converter
SOC	State of Charge
SPS	Simulink-to-Physical Signal
SPRC	Series-Parallel Resonant Converter
SRC	Series Resonant Converter
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

LIST OF SYMBOLS

A	Ideality Factor of the Diode
c	Step Size
C	Capacitance
C_{bat}	Capacity of the Battery in Ahr
C_p	Parallel Capacitance
C_s	Series Capacitance
D	Duty Cycle
dI	Change in Current
dP	Change in Power
dV	Change in Voltage
dt	Change in Time
Δd	Small Change in Duty Cycle
ΔV	Small Change in Voltage
e	Permissible Error
E	Fundamental Input Voltage
E_g	Band Gap Energy
f_n	Normalized Frequency
f_p	Pole Resonant Frequency
f_r	Resonant Frequency
f_s	Switching Frequency
G	Solar Irradiation
I	PV Array Output Current
I_d	Cell Reverse Saturation Current
i_{D1}	Secondary-Side Diode Current
I_{in}	Input Current
i_{Lr}	Resonant Inductor Current
i_{Lm}	Magnetizing Inductor Current
i_{Lm0}	Magnetizing Inductor Current at time t_0

I_{max}	Maximum Charging Current
I_{out}	Output Current
I_{ph}	Cells Photo Current
$I_{p,f}$	Fundamental Primary Current
I_{pv}	PV Module Output Current
I_{rr}	Reverse Saturation Current at T_r
I_{sc}	Short-Circuit Current
I_{scr}	Cell Short Circuit Current
$I_{in,sense}$	PV Panel Sensing Current
k	Boltzmann's Constant
k_i	Short-Circuit Current Temperature Coefficient
L	Inductance
L_r	Resonant Inductance
L_m	Magnetizing Inductance
L_n	Inductance Ratio
M	DC Gain
n	Transformer Turn Ratio
N_p	Number of Modules Connected in Parallel
N_s	Number of Cells Connected in Series
P	PV Array Output Power
$P_{in,max}$	Maximum Input Power
P_{MPP}	Peak Power Point
q	Electron Charge
Q	Quality Factor
R	Resistance
R_{eq}	AC Equivalent Load Resistance
R_{in}	Input Resistance
$R_{in,fs2}$	Input Impedance at the Boundary between ZCS region and ZVS Region
$R_{in,fs1}$	Input Impedance at Region $dP/dV > 0$

$R_{in,fs2}$	Input Impedance at Region $dP/dV < 0$
R_{MPP}	Resistance at Maximum Power Point
R_L	Load Resistance
R_o	Output Resistance
R_s	Series Resistance
R_{sh}	Shunt Resistance
T	Cell Temperature
$t_{d,min}$	Minimum Dead Time
T_r	Cell Reference Temperature
T_s	Switching Period
V	PV Array Output Voltage
v_{ab}	Primary-Side Bridge Voltage
V_{bat}	Battery Voltage
$V_{bat,sense}$	Battery Sensing Voltage
$V_{bat,min}$	Minimum Battery Charging Voltage
v_{cd}	Secondary-Side Bridge Voltage
v_{cr}	Resonant Capacitor Voltage
v_{cr0}	Resonant Capacitor Voltage at time t_0
V_d	Voltage Drop of Output Diode
v_{ds}	Voltage across MOSFET
V_{in}	Input Voltage
$V_{in(max)}$	Maximum Input Voltage
$V_{in(min)}$	Minimum Input Voltage
$V_{in(nom)}$	Nominal Input Voltage
$V_{in,sense}$	PV Panel Sensing Voltage
V_{max}	Maximum Charging Voltage
V_{MPP}	Voltage at Maximum Power Point
V_o	Output Voltage
$V_{o,ac}$	AC Equivalent Output Voltage

V_{oc}	Open-Circuit Voltage
$V_{o(max)}$	Maximum Output Voltage
$V_{o(min)}$	Minimum Output Voltage
$V_{o(nom)}$	Nominal Output Voltage
$V_{p,f}$	Fundamental Primary Voltage
V_{pv}	PV Module Output Voltage
V_{ref}	Reference Voltage
ω_r	Radian Frequency
X	Reactances

PENGESANAN TITIK KUASA MAKSIMUM DENGAN MENGGUNAKAN PENUKAR SALUNAN LLC UNTUK SISTEM KUASA PV

ABSTRAK

Pengesanan titik kuasa maksimum (MPPT) merupakan salah satu bahagian yang penting dalam pelbagai sistem fotovoltan (PV) dan telah dikaji dengan teliti dalam kajian lepas. Walau bagaimanapun, kebanyakan sistem pengesanan titik kuasa maksimum menggunakan penukar DC-DC permodulatan lebar denyut. Baru-baru ini, penukar salunan DC-DC menjadi terkenal untuk pemprosesan kuasa kerana mempunyai ciri-ciri yang baik seperti kehilangan pensuisan yang rendah, operasi frekuensi tinggi dan gangguan elektromagnetik yang rendah. Dalam penyelidikan ini, algoritma pengaliran tambahan (INC) dicadangkan dengan menggunakan penukar salunan LLC untuk pengesanan titik kuasa maksimum dalam sistem kuasa PV. Penukar salunan LLC mampu mengesan kuasa maksimum semasa beroperasi dengan pensuisan sifar voltan mengakibatkan kecekapan yang tinggi untuk operasi frekuensi tinggi. Selain itu, INC MPPT dengan mod voltan malar (CV) untuk pengecasan bateri dicadangkan dalam kajian ini. Pelaksanaan terperinci MPPT dengan mod CV algoritma dan carta aliran serta prosedur reka bentuk penukar dibincangkan dengan teliti dalam tesis ini. Keputusan eksperimen prototaip 100W menunjukkan bahawa penukar mencatat kecekapan puncak setinggi 81% untuk keseluruhan julat reka bentuk. Sebagai tambahan, penukar juga mempamerkan prestasi yang baik dalam menguasai kuasa maksimum di bawah pelbagai keadaan persekitaran sambil menonjolkan keupayaan pensuisan lancar.

MAXIMUM POWER POINT TRACKING USING LLC RESONANT CONVERTER FOR PV POWER SYSTEMS

ABSTRACT

Maximum power point tracking (MPPT) is a crucial part in any photovoltaic (PV) systems and is thoroughly addressed in the literature. However, most of the existing MPPT systems use pulse-width modulated DC-DC converters. Recently, resonant DC-DC converters have become famous for power processing due to their good characteristics such as low switching loss, high frequency operation and low electromagnetic interference. In this research work, an incremental conductance (INC) MPPT using LLC resonant converter is proposed for PV power systems. The LLC resonant converter can track the maximum power while operating in zero voltage switching region resulting in high efficiency for high frequency operation. In addition, an INC MPPT with constant voltage (CV) mode for battery charging is proposed in this study. Detailed implementation of the MPPT with CV mode algorithm and its flowchart as well as the design procedure of the LLC resonant converter is thoroughly discussed in this thesis. The experimental results of a 100W prototype shows that the converter obtains a peak efficiency of 81% for the entire design range. In addition, the converter exhibits good performance in capturing the maximum power under various environmental conditions while performing soft-switching capabilities.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Presently, the world energy is still predominantly generated by fossil fuel. Liquid fuel, coal and natural gas are the main sources of energy as shown in Figure 1.1. However, the world experiences severe global warming and climate change due to the extensive burning of fossil fuels for power generation in order to meet the growth of the world energy demand. The main cause of global warming is the emission of greenhouse gases, and the primary source of these gases is from fossil fuel burning (Committee on the Science of Climate Change of National Research Council, 2001; Oreskes, 2004). Furthermore fossil fuels are non-renewable resources. So it would be difficult to meet its ongoing demand (Owen, Inderwildi, & King, 2010). As a result of the said environmental issues, more researches are being pursued by related organizations for more efficient and green power generations. Renewable energies such as solar photovoltaic (PV), wind, wave, biomass and etc. are of great interest in research. The renewable energies are clean, inexhaustible and does not release greenhouse gases (Committee on the Science of Climate Change of National Research Council, 2001; Oreskes, 2004).

Over the past ten years, renewable energy has seen rapid technology advances and increasing deployment throughout the whole world. By adopting and shifting to renewable energy, we can reduce greenhouse emission and meet the increasing world energy demand. Furthermore, renewble energy helps mitigate future extreme weather

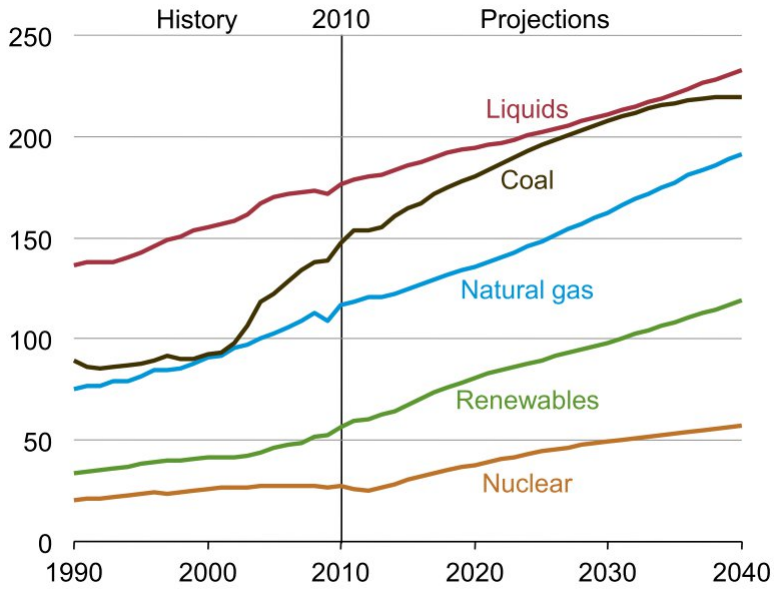

Figure 1.1: World energy consumption by fuel type, 1990-2040 (quadrillion Btu) (U.S. Energy Information Agency, 2013)

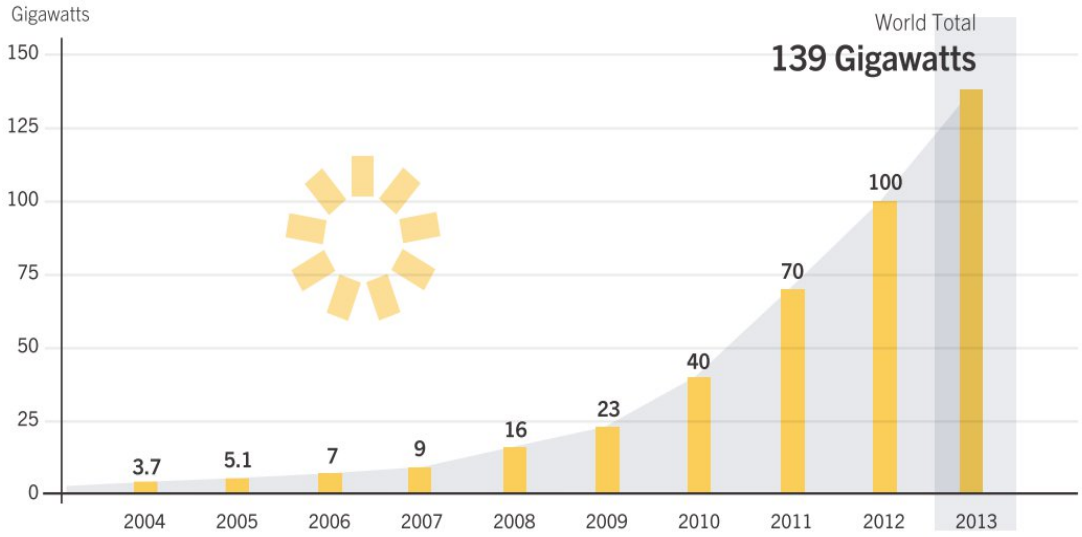

Figure 1.2: Solar PV total global capacity, 2004-2013 (Brower et al., 2014)

and climate changes. Through technological advances, timely and cost-efficient delivery of energy can be achieved (Ellabban, Abu-Rub, & Blaabjerg, 2014). In 2013, for the first time, new solar PV power capacity added surpassed the new wind power capacity added. Solar PV has continued to expand at a enormous rate, with a growth in global capacity averaging almost 55% annually over the past five years. In 2013, the world total solar capacity is at 139 GW as shown in Figure 1.2. From Figure 1.3,

China added the most PV capacity followed by Japan and United States (Brower et al., 2014).

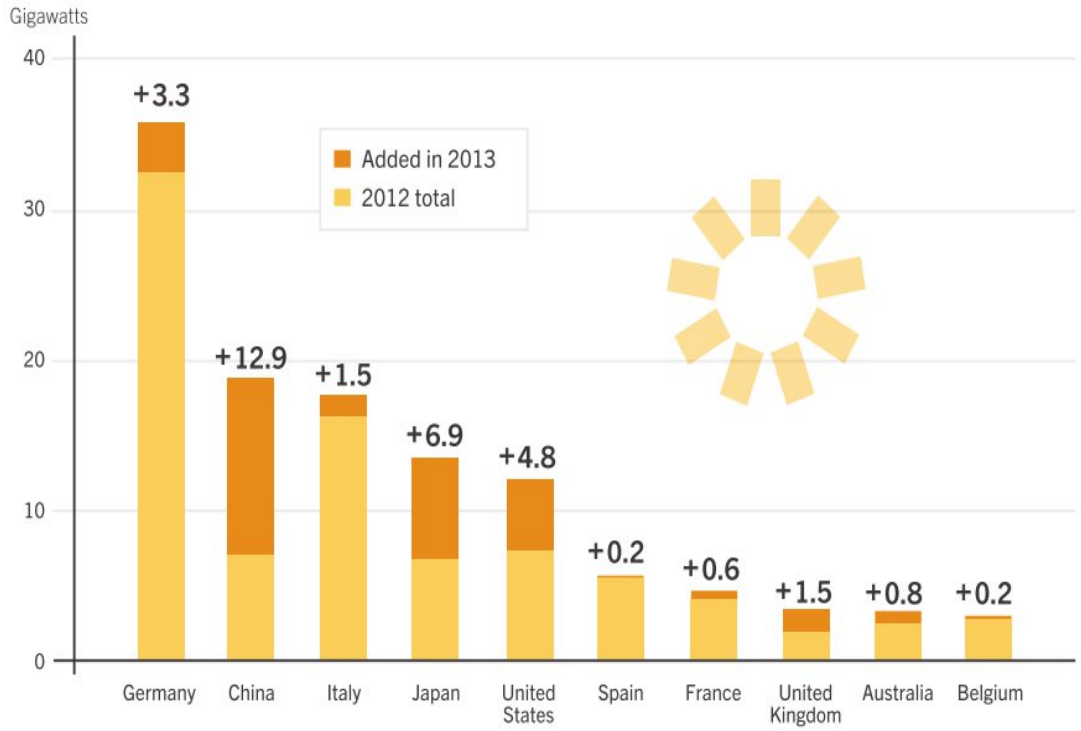

Figure 1.3: Solar PV capacity and additions, top 10 countries, 2013 (Brower et al., 2014)

Policy support from over 50 countries have been available for PV adoption and expansion such as PV feed-in tariffs (Hoppmann, Huenteler, & Girod, 2014; Zhi, Sun, Li, Xu, & Su, 2014). However the recent significant increase of PV usage is mainly due to rapid cost reductions of the PV as well as latest technology advancements that overcame some of the limitations that PV previously had. Conventional silicon cell (c-Si) modules are the most expensive PV technology, but they have the highest commercial efficiency. The global price for c-Si modules from 2004 to Q3 2008 is hovering around $3.50-$4.00/W. In 2009, facing steep price-point competition from thin-film (CdTe,CIG/CIGS) solar module, the price of c-Si modules dropped rapidly to $2.00/W and still manufacturers are able to make positive operating margin (Bazilian et al.,

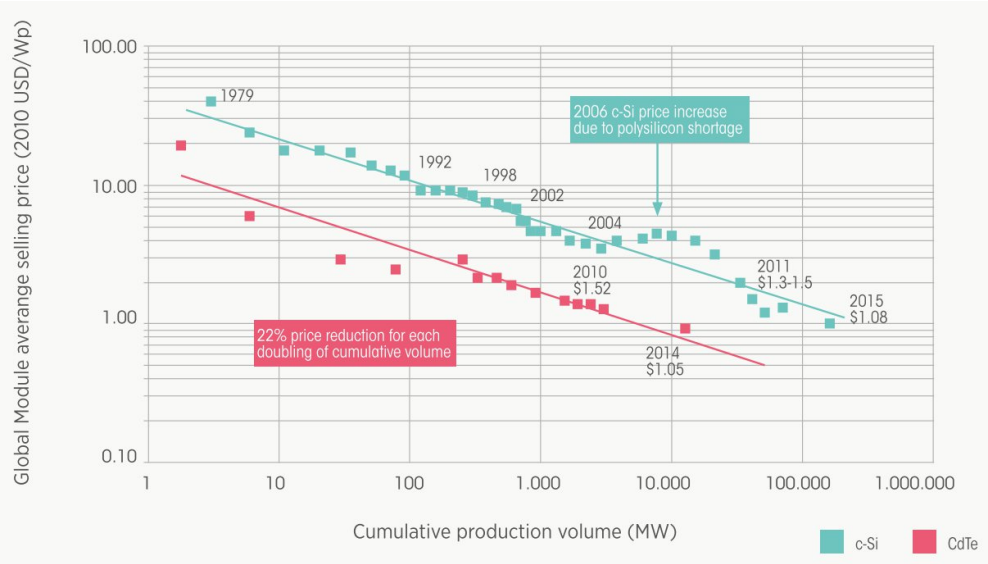

Figure 1.4: The global PV module price learning curves for c-Si wafer-based and CdTe modules, 1979 to 2015 (Agency, 2012)

2013). This success was due to the reductions in costs achieved over the past four years from technology advances and growing scale of production in wafer, cell and module manufacturing processes. Improved performance resulting from better cell efficiencies and lower electrical conversion losses also help in driving the cost down. In April 2012, c-Si PV modules fell below $1.00/W. In March 2012, thin film module price ranges between $0.79/W for Cds/CdTe to $0.92/W for a-Si/μ-Si modules (Bazilian et al., 2013). Top Chinese producers are fast approaching costs of $0.50/W for c-Si modules in 2013 (Brower et al., 2014), clearly outperform the projected price done by International Renewable Energy Agency in June 2012 shown in Figure 1.4 (Agency, 2012). With the affordable price of PV modules, solar energy has the potential to be a great contributor in fulfilling the world energy demand and reducing greenhouse gases emission.

A basic block diagram of a PV power generation system suitable for residential homes is shown in Figure 1.5 (Mutoh et al., 2006). It consists of a PV array, a DC-DC